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The aerodynamics of sailing apparel

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Abstract

The paper presents the effect of changes in sailing apparel on aerodynamic drag, starting from the assumption that drag reduction of sailing apparel will increase the speed of an Olympic class sailing boat (in this case the Laser, a single-handed Olympic dinghy), mainly on upwind courses. Due to the fact that literature on this specific subject is non-existent, a theoretical framework on hydrodynamic and aerodynamic drag of the sailing boat and sailor had to be set-up to provide us with ball park figures on the effect of changes in sailing apparel. It showed that the aerodynamic drag caused by the sailor was around 12% of the total drag (aerodynamic and hydrodynamic). This also demonstrated the room for improvement. Next, the actual aerodynamic drag of eight different combinations of state-of-the art sailing apparel was measured in the wind-tunnel (TUDelft Open Jet Facility) at various wind angles and wind speeds (up to 17 ms^{-1}). The experimental results were then compared to the results of the theoretical framework. The results of the experiment show a maximum difference of 11% in aerodynamic drag between the best and worst case scenario (at 8.2 ms^{-1} wind speed). This reduction of the sailors' aerodynamic drag is estimated to reduce the total (sailor + sailing boat) drag by 1.2%.

Keywords: Aerodynamics; sailing apparel; wind-tunnel experiment

1. Introduction

Winning an Olympic class sailing medal basically comes down to two things: sailing fast into the right direction and to do this consistently better than your competitors. In practice however, this requires many years of training in order to improve boat speed and tactical insights. Increasing the boats' speed can be done either by improving the propulsion by means of sail trim or, by converting this propelling force into speed more efficiently or by means of drag reduction. In general, the focus in this last area was on reducing the hydrodynamic drag of the ship's hull, rudder and dagger board. To the authors, no prior research is known into the aerodynamic drag on Olympic class sailing boats. Prior research into the

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aerodynamics of sports garment however showed that differences in aerodynamic drag between several types of garment can be quite dramatic; Chua et al [1] reported a difference of a factor 1.5 in the aerodynamic drag coefficient between flapping and tight fitting textiles.

The relative effect of the aerodynamic drag induced by the sailor is highest with small boats at high speeds and also the negative effect of the sailor-induced aerodynamic drag is highest at windward (close-hauled) courses. The smallest Olympic boat is the 14-ft Laser(see figure 1), it is also a class with large numbers of competitors and leaves –due to strict class regulations- no room for changes in the hull and rigging. Therefore we used this boat as reference during this research project and focus on windward courses (apparent wind angle 30˚) at a boat speed of 4.3 knots (2.2 ms^{-1}).

Fig. 1. Laser class sailboat with sailor, sailing upwind/close-hauled (over port)

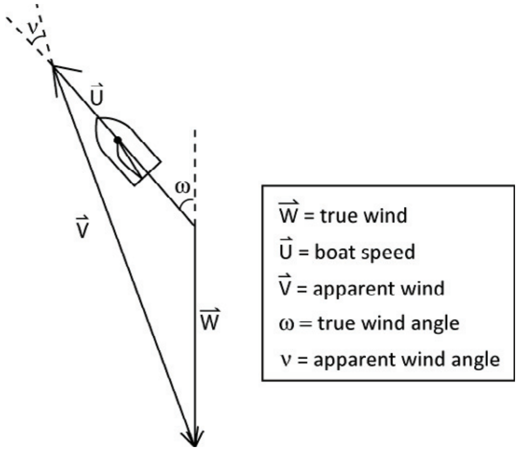

Fig. 2. Speed vector diagram describing the situation of close-hauled sailing (over port)

1.1. First estimates: what factors contribute to the total drag force on a sailing boat and how do they compare?

Before starting the experiment, we conducted a desk search in order to get a feel for the magnitude of the various factors determining the total drag force on a sailing boat divided over:

- - Hydrodynamic drag induced by the boat parts under water: hull, rudder and keel/daggerboard
- - Aerodynamic drag induced by the hull above the waterline
- - Aerodynamic drag induced by the rigging; mast, boom, sail(s)
- - Aerodynamic drag induced by the sailor

The hydrodynamic drag of the hull of a Laser class sailboat (including rudder and daggerboard) was estimated with an approximation method based on “The Delft Systematic Yacht Hull Series” (DSYHS)[2]. This method was validated for small sailing boats and boat speeds up to 7 kn (3.6 ms^{-1}) with a towing tank experiment using the hull of a Flying Dutchman (FD) sailing boat (the FD is 20-ft, 2-person former Olympic sailing class). The hydrodynamic drag estimation was increased by 10% (estimation by author) in order to compensate for the effect of leeway. The effect of heeling on hydrodynamic drag was not included.

The aerodynamic drag induced by an object can be estimated using the drag equation:

$$F_D = \frac{1}{2}\rho V^2 C_D S \tag{1}$$

With:

F_D : magnitude of rag force [N]
ρ : mass density of air [kgm^{-3}]
V : relative speed [ms^{-1}]
C_D : drag coefficient
S : projected area [m^2]

In literature, values for the drag coefficient (C_D) for the part of a vessel that extends above the water can be found ranging between 0.5 and 0.7 [3]. It must be noted that the values mentioned refer to "high speed vessels" and will most probably differ from the values that apply to a Laser class sailboat. We assumed a C_D-value of 0.6 for the hull only. The projected area of the hull is determined using a CAD model of a Laser class sailboat [4] (heeling neglected). The resulting area (above the designed waterline) was 0.532 m^2.

Wind tunnel tests on a 1:16 scale model of a Laser class sailboat showed that sailing upwind (apparent wind speed of 7 ms^{-1}, apparent wind angle of 30.4°, centerline-boom angle δ of 5°) results in an aerodynamic drag coefficient for the rigging ($C_{D(rigging)}$) of 0.5 [5]. In this situation the projected area of a standard Laser sail (with an area of 7.06 m^2) would be 2.98 m^2. Specific data on drag coefficients could not be found for sailors (nor for similar positioned athletes). For a cyclist on a bicycle the value of C_D varies between 0.88 and 1.15 depending on position and clothing [6]. Based on the values found in literature a value of 1 will be assumed for $C_{D(sailor).}$ The estimated projected area of the sailor is 0.4 m^2 (based on CAD model of male adult, confection size 50 (L)). Combining the various factors mentioned above resulted in a first estimate of the total drag force on the Laser sailing boat. The relative influence of the various factors is represented in the graph below:

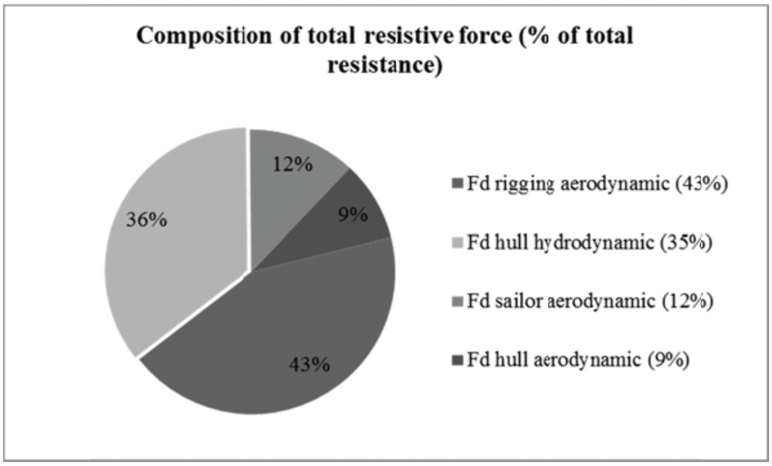

Fig. 3. Composition of resistive force, as a percentage of the total resistive force, on a Laser class sailboat when sailing close-hauled, at a speed of 2.2 ms^{-1}, at an angle of 40° with the true wind, and with a true wind speed of 6.2 ms^{-1}

The desk research resulted in an approximation for the total resistive force on the Laser sailing boat of 135 N. According to the estimate the aerodynamic drag induced by the sailor accounts for about 10% of the total resistive force. This implies that lowering $F_{D(sailor)}$ in this situation by about 10% will result in a decrease of the total resistance of about 1%.

2. Experimental set-up

The wind-tunnel experiment was conducted in the TUDelft Open Jet Facility (OJF). We measured the resistive force of a full-size mannequin wearing eight different sets of sailing apparel consisting of the following components: wet-suit, life-jacket, dry-suit, cap/sun visor and lycra shirt(see figure 4). The resistive force on the mannequin was logged at wind speeds from 2 to 17 ms^{-1} according the OJF measurement and data processing protocols and corrected for the influence of the mounting pole.

Fig. 4. Magic Marine sailing apparel tested. From left to right: mannequin wearing ultimate 4/3 wet-suit, regatta breathable dry-suit, pro neo life-jacket, mannequin wearing the summer pants (cube lycra set) and lycra shirt over the pro neo jacket and the sun visor

Fig. 5. The test setup during testing (mannequin is now wearing wet-suit + life-vest

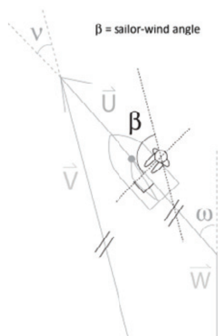

Fig. 6a. (left) When the apparent wind angle (ν) is 30˚, the angle between the sailor and the apparent wind (β) will be 120˚

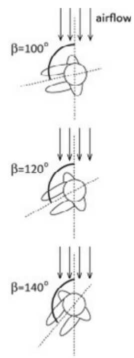

Fig. 6b. (right) Tests were conducted at three different apparent wind angles (β); 100˚, 120˚ and 140˚

3. Experimental results

The experimental results consists of data on aerodynamic drag forces for eight different apparel set-ups for apparent wind-speeds from 2 – 17 ms^{-1} at three different angles to the apparent wind vector (β=100˚, 120˚ and 140˚). The graph below presents the computed results of $F_{D(sailor)}$ for β=120˚ .

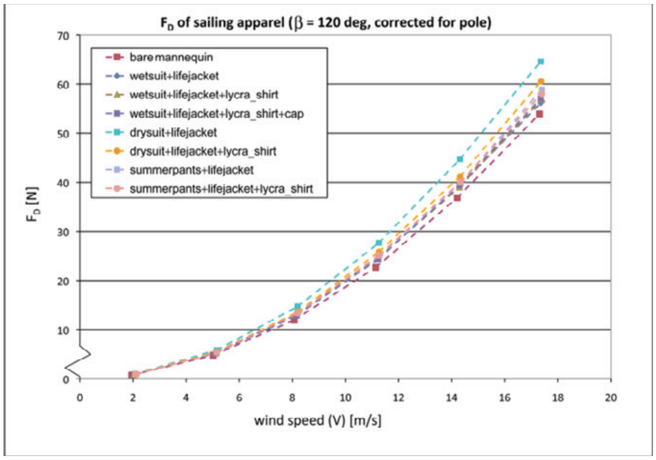

Fig. 7. Computed values for $F_{D(sailor)}$, consisting of $C_D.S$ ($S_{120} = 0.44$ m^2) for eight different combinations of sailing apparel. Corrected for the mounting pole, angle β of 120˚, apparent wind speeds from 2 – 17 ms^{-1}

The relative difference in aerodynamic drag force, normalized for the set-up in which the drag of the mannequin only was measured, allows us to compare the different combinations of sailing apparel. This is represented in the next figure.

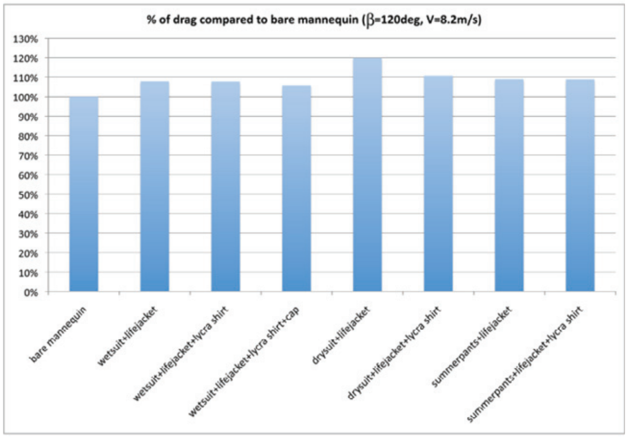

Fig. 8. Relative aerodynamic drag force of different sets of apparel when compared to bare mannequin with β = 120˚ and V = 8.2 ms^{-1} ('bare' mannequin = 100%)

4. Conclusions

A sailor wearing a dry-suit + life-jacket will experience a 11% higher aerodynamic drag than a sailor wearing a wet-suit + life-jacket. Wearing a lycra shirt over his dry-suit and life-jacket will alleviate this increase of aerodynamic drag with about 8% (at β = 120˚ and V = 8.2 ms^{-1}). Wearing a lycra shirt on top of a wet-suit + life-jacket does not lower the aerodynamic drag on the sailor. Differences are insignificant (<1%). A sailor wearing a lycra summer outfit + life-jacket does not necessarily experience a lower aerodynamic drag. The difference is insignificant (<1%)(at β = 120˚ and V = 8.2 ms^{-1}). A change in the sailors' position (angle β) with 20 degrees has as significant effect on the aerodynamic drag. In the vast majority of settings, this effect is larger than the actual choice of apparel (the only exception is when comparing the “dry-suit + life-jacket” configuration to any of the other configurations).

The desk research led to the conclusion that the relative contribution of the aerodynamic drag of the sailor to the total drag on a laser class sailboat, sailing upwind at a speed of 2.2 ms^{-1}, at a true wind angle of 40^o, and a true wind speed of 6.2 ms^{-1}, is in the order of 10%. The experimental research showed that the difference in aerodynamic drag between a sailor wearing a dry-suit and a sailor wearing a wet-suit is also in the order of 10%. Combining these results leads to the general conclusion that wearing a dry-suit or a wet-suit in this situation has a relative influence in the order of 1% on the total resistive force on the sailboat. Because of the quadratic influence of the speed on the resistive force, this implies a speed difference even smaller than 1%.

5. Discussion

The difference between the aerodynamic drag of the wet-suit and the drysuit configuration was in the order of 10%. This is not as large a difference as the factor 1.5 found by Chua [1]. This difference can probably be explained by the fact that the dry-suit was not flapping during the tests (the drysuit was tighter fitting than the samples used by Chua et al. and probably also more rigid). The test results show that the aerodynamic drag of the summer outfit is in the same range as the aerodynamic drag of the wet-suit configuration. A possible explanation could be that the wet-suit disturbs the airflow around the legs of the mannequin, resulting in a lower drag. Experiments performed in the past at the OJF with ice skating apparel pointed out that the airflow around the legs forms a substantial part of the total aerodynamic resistance around a human body.

Based on values that can be found in literature [6], the aerodynamic drag coefficient of the mannequin should be between 0.9 and 1.2. Based on a CAD model that resembles the mannequin an estimate was made of the value for S for each value of (see appendix B). When S is known C_D can be calculated. At $\beta = 120^\circ$ this results in an estimated value for C_D of 0.72 for the bare mannequin at a wind speed of 8.1 ms^{-1}. This is somewhat lower than the values found in literature. This difference could be caused by the extremely smooth surface of the mannequin; the values mentioned in literature were for a man wearing clothes.

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